FLUX RESET IN MAGNETIC AMPLIFIER CORES

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Abstract.—Performance quality control of magnetic amplifiers has improved recently but it still remains one of the pressing problems facing industry today. Magnetic amplifier performance is determined basically by the flux resetting characteristic of the core material. Quality control is discussed along with core testing and it is shown how the B-H relationship is dependent upon time (history).

The flux resetting characteristics are presented for different core materials, including the newly developed material "Dynamax". This includes the rate of change of flux when a step function of mmf (oersteds) is applied. The relationship between such data and operating hysteresis loops is discussed and differences caused by modification of annealing cycles are shown.

I. INTRODUCTION

Quality control of magnetic amplifiers has made fair progress in the last few years. Rectifier characteristics, including aging, have constituted a major limitation. Where increased cost is acceptable, rectifiers are now available (or soon will be) which are capable of relaxing this limitation on quality control in the bulk of applications expected. Relaxing this limitation can be expected to leave the vagaries of the core characteristics as the major limitation on magnetic amplifier quality control. Notable exceptions can, of course, be named.

In the past five years the vagaries of core characteristics have tended to play the lesser role simply because cores have been purchasable with a degree of uniformity surpassing that of rectifiers where aging and temperature changes are considered. Such uniformity was difficult to achieve in production, and certainly far from an inherent expectation. The various test methods by which core grading and quality control were achieved will be discussed later along with possible improvements foreseen for the future.

With regard to the future, in a great many applications the limitations on magnetic amplifier quality control appear to rest on methods of predicting core performance in given circuits. Core grading and test methods in current use leave much to be desired. Why this is so and what can be done about it is not widely enough understood in spite of a few outstanding papers, such as that of Roberts presented last year[1], expanding the work of Conrath.[6] Perhaps this is because more emphasis has been given to mathematical analysis of theoretical magnetic amplifier models than actual behavior of cores and rectifiers.

It is the basic mission of this paper to promote a better understanding of the core flux reset phenomenon as it *actually occurs*, not as it is generally assumed to be. Many excellent papers have been presented on the theoretical analysis of magnetic amplifiers of all basic types, and early this year a text book[2] by Storm was published which gives broad coverage of the subject. In order to present any mathematical analysis of magnetic amplifier operation it is necessary to write a generalized equation or equivalent circuit describing the various components. For example, in the case of cores, some sort of hysteresis loop is always assumed. In some writings[9] it is an idealized rectangle, quite an ex-

treme of simplification. In others,[2,3] more complicated forms, such as parallelograms with minor loops, are considered. When rectifier characteristics are considered in these analyses it is typical to represent the reverse leakage as simply a shunt resistor. Some treatments even leave leakage as an undefined function of rectifier voltage, basing the analysis on whatever average value of leakage current over the cycle happens to exist at the particular operating point under consideration. Such over-simplifications are certainly in order for the sake of analysis; in fact, they tend to make the analysis even more elegant and easy to follow. But in turning from mathematical analysis of theoretical models to quality control over production amplifiers, it is clear such simplifications are totally out of order. Cores and rectifiers simply do not behave this way. Much more work needs to be done on methods of grading, rating, and expressing characteristics of either cores or rectifiers, as well as work on methods predicting amplifier characteristics on the basis of such ratings.

II. ON THE MECHANICS OF FLUX CHANGE

The theoretical mechanics of operation of magnetic amplifiers has been so well analyzed in many papers and the previously mentioned text[2] on the subject that no attempt will be made here to present again this basic work. Such writings are already familiar items to those interested in the design and quality control of magnetic amplifiers.

As previously mentioned, all of these theoretical analyses use some form of idealized hysteresis loops. To do otherwise would unnecessarily complicate the analysis without promoting further understanding of the basic theory. However, cores do not behave in this fashion. For this reason, practical quality control begins where these analyses end. No argument is found with basic theory of operation, the problems of quality control and amplifier design centering instead around the departure of the flux-mmf relationship from the assumed loops.

Flux level in a core is not only a function of applied mmf, but also a function of mmf as it varies with time, and of previous flux history. In a practical core flux cannot be moved from one level to another instantly, even if the allowed induced voltages were without limit. The conventional concepts of eddy currents are only a partial explanation at best. The theory of magnetism appears to be extremely complicated, and our understanding of it is meager indeed. A general expression for flux vs. mmf does not seem to be known at the present time. Instead we are forced simply to observe experimentally what happens to the flux as we apply different conditions of mmf and time to a core. Since we are unable to write any general expression for the flux as a function of time and mmf, it is natural to set up some arbitrary test procedure and attempt to measure basic magnetic characteristics of cores in terms of one or more of the following artifices:

1. D-c hysteresis loop.
2. Dynamic hysteresis loop using whatever current is necessary to produce a sine wave of induced voltage.
3. Dynamic hysteresis loop using a sine wave of current for excitation.

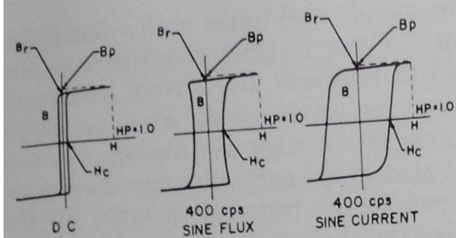

Fig. 1—Three types of hysteresis loops taken on a typical Deltamax core (Courtesy Arnold Engineering Co.).

These three methods are shown in Fig. 1, and produce strikingly different loops as might be expected. As was previously implied, these three loops give little clue as to what performance might be expected under different conditions of excitation.

It is extremely difficult to visualize the inter-relationships between flux, mmf, and time in Fig. 1 (B) and 1 (C) since a sinusoidal function is involved. Consider instead of a sinusoid the application of a fixed value d-c step of exciting current to a previously saturated core, such as Orthonol (Deltamax). At first thought one might expect staggering voltages, but actually nothing like this occurs. Instead Figs. 2(A) and 2(B) show that the flux starts moving, gathering speed fairly quickly until the flux has reset about 25 percent of the way; from there on it slows down more or less gradually. This was taken from the work of Lord and Huhta, showing the rate of change of flux (induced emf) for a given fixed (direct) exciting current in a two mil 1/2″ wide tape core of Deltamax (Orthonol). In Fig. 2(A) note that each curve shows the rate of change resulting from the *same* fixed mmf when the initial flux level is varied prior to closing the switch.[a] It is rather startling that when the flux has been at reset at the 50 percent level, the same fixed mmf suddenly applied will produce approximately twice the rate of change that is observed when the flux was started at zero percent level, just coming out of saturation. Other samples of Deltamax (Orthonol), as well as other core materials, may have very different patterns; note Fig. 2(B). For a given fixed mmf, the rate of change of flux will always

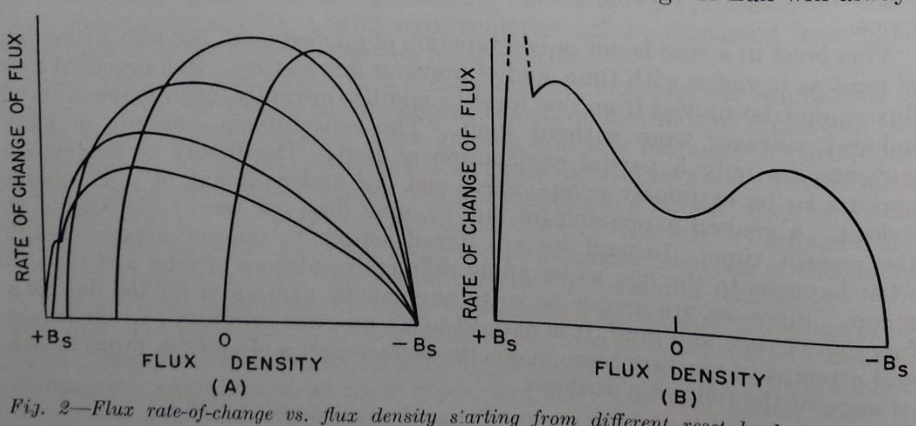

Fig. 2—Flux rate-of-change vs. flux density starting from different reset levels at constant mmf for two different Deltamax samples.

[a] It is important to know the previous history of the flux prior to its coming to rest at the various starting points in Fig. 2. To take these oscillograms the flux was returned from negative saturation only up to these initial starting points; i.e., it was never reversed in direction during the return excursion.

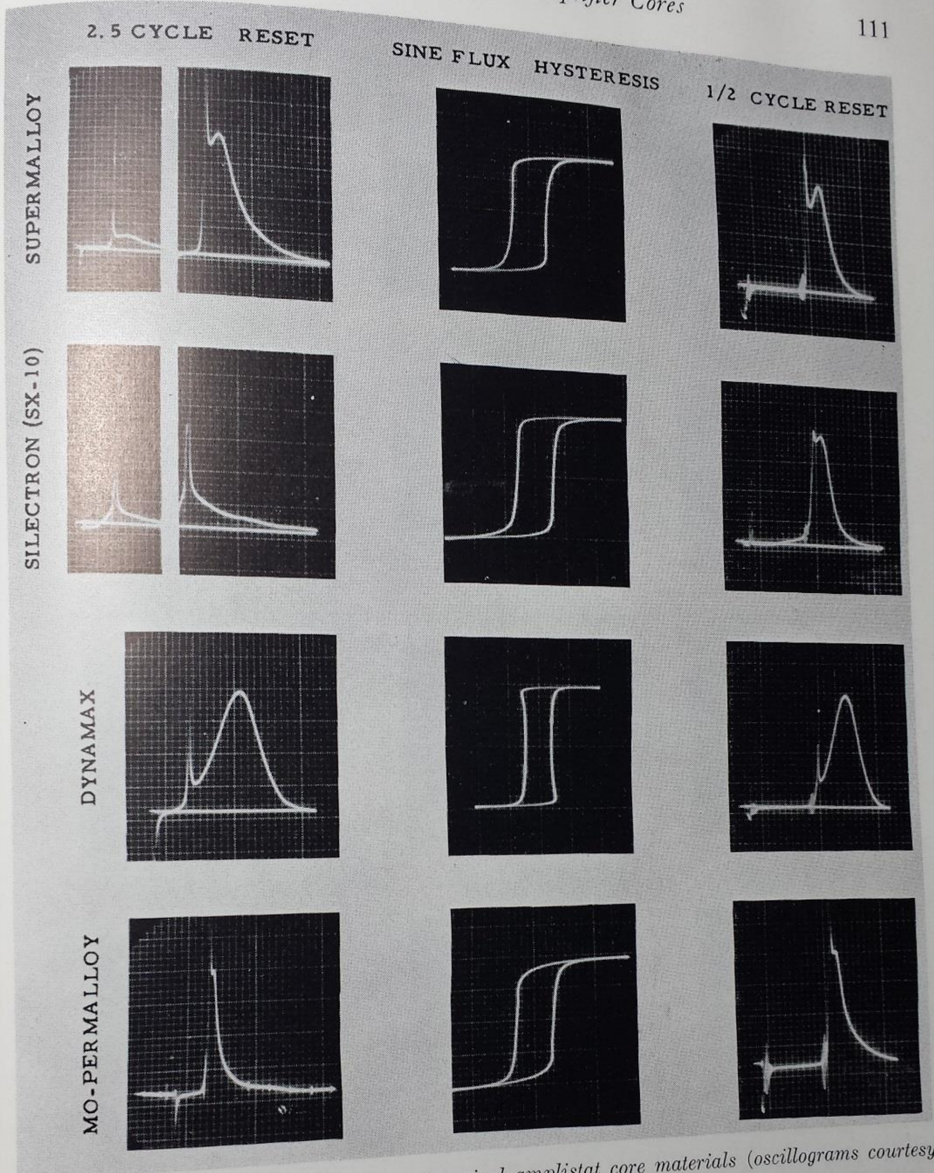

Fig. 3—Flux resetting characteristics of typical amplistat core materials (oscillograms courtesy P. A. Fessler).

vary with the flux level as well as with the initial level at which the step function of mmf was applied and its previous history. What is even more confusing, so far as writing an expression for flux is concerned, is that this previous history of flux motion preceding an incremental change fairly well dominates the rate of change of flux, dB/dt, observed.

As was pointed out by Huhta[4] and by Lord, different core materials have very different flux resetting characteristics. To illuminate the point, Fig. 3 is presented showing an oscillographic comparison of popular core materials. On

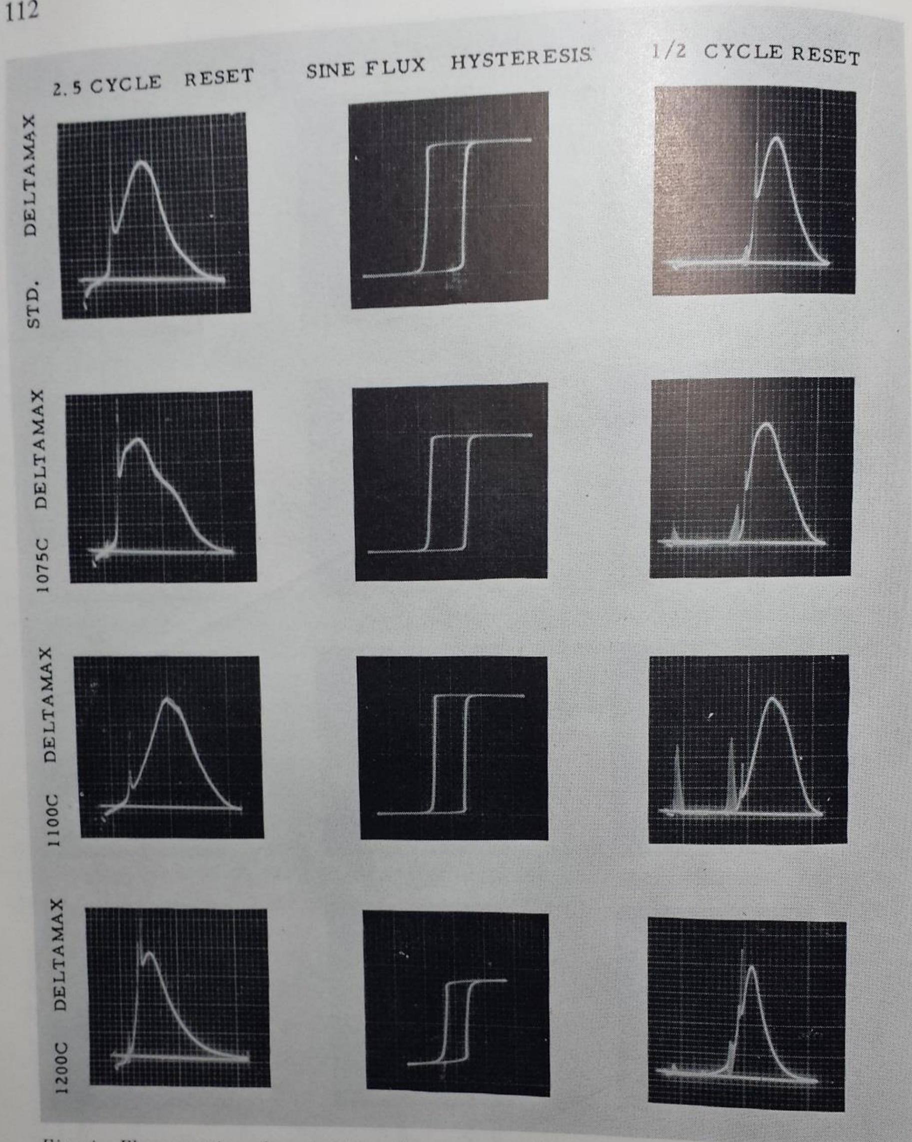

Fig. 4—Flux resetting characteristics of four samples of Deltamax (oscillograms courtesy of P. A. Fessler).

the Y-axis the left hand column shows the induced reset voltage (dB/dt) as the core flux resets from $+B_{MAX}$ to $-B_{MAX}$ in 42 milliseconds (2.5 cycles) at constant mmf. Time is represented on the X-axis. Note in these photos that the scope trace is clamped near zero during the first half cycle while the core flux is driven thoroughly into saturation by the circuit. The middle column shows the 60-cycle sine flux hysteresis loop for the particular material. The right hand column shows reset flux rate-of-change pattern vs. constant but larger mmf; it is similar to the left hand column except that the flux is reset in eight milliseconds (half

cycle). In the supermalloy and SX-10 samples the induced voltage is so high at the start that the oscilloscope beam was driven off-scale. To show the extreme height of this spike another photo was taken with the Y-axis gain reduced. This is shown in the insert at the extreme left for the sake of comparison.

Various samples of a given core material also may show pronounced differences. Four samples of Deltamax (Orthonol) are shown in Fig. 4, portrayed in the same manner as described above for Fig. 3. Two of the samples could be considered normal, one is over-annealed, and one is under-annealed.

Note that the hysteresis loops give little clue (Figs. 3 and 4) to the reset characteristic.

III. RESETTING THE CORE FLUX

Quality control aspects of the flux resetting characteristics require consideration of the circuits in which the cores are to be employed, as well as whether the operation employed will be in the high impedance mode or the low impedance mode. References 1, 2 and 3 give an excellent theoretical foundation for considering these aspects. But the design and quality control engineer must now go further and consider the core operation as it actually exists. This is difficult because the state of the art today provides no formulae, no derivable expressions for flux vs. mmf vs. time, etc. Therefore, those pursuing the design and quality control art must decide for themselves what test criteria are applicable and economically useful in their specific problems.

So far this paper has shown something of the peculiar nature of flux reset which exists. Knowledge of its existence will suggest to the engineer where to look further, and how to look further for factors which will influence the performance of his product.

The circuit mechanics involved in resetting the core flux have been thoroughly analyzed elsewhere [1,2,3,4,9]. Some review of the subject is in order here along with discussion of the simplest case as an example of circuit influence on quality control techniques. Among the most common amplistat circuits encountered in modern equipment are the following general categories:

A. Full wave, single ended, low impedance d-c control circuit.
B. Full wave, single ended, high impedance d-c control circuit.
C. Full wave, push pull, d-c control circuit.
D. Full wave, single ended, a-c input.
E. Half-wave circuits.
F. The so-called "Ramey-type" circuits.

Of the six arbitrary classes above, the circuit operation of only one is closely allied with a "hysteresis loop". Storm has shown that in practical amplifiers the resetting operation follows very closely a sine wave of flux[2]. Fortunately, this special circuit case is one of the most widely used today.

Of the other five principal classes referred to above, the circuit operation moves the flux in a fashion that bears little if any resemblance to a sine wave of either flux or voltage. To set up a working model on which reset problems caused by circuit operation can be illuminated, let us consider the bi-phase circuit, Fig. 5. The effect of several different amplistat circuits on so-called "operating hysteresis loops" has been covered in detail by Lord.[3] The bi-phase circuit in the high control circuit impedance mode is typical of case (B) above.

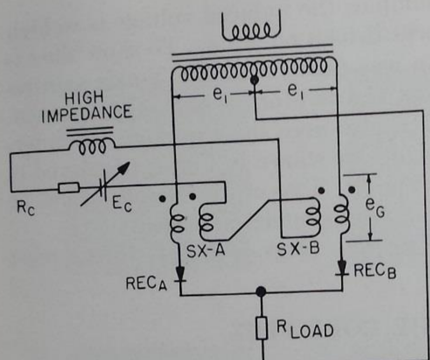

Fig. 5—Bi-phase (or center-tap) amplistat circuit.

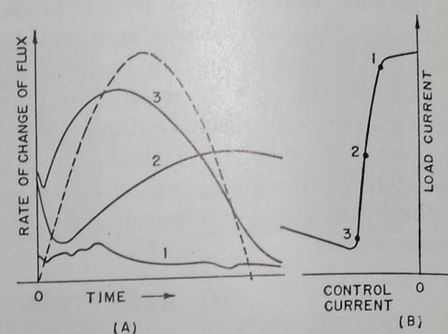

Fig. 6—Unrestricted flux rate-of-change compared to amplistat performance for constant mmf.

In this mode, the first and principal portion of the flux reset usually occurs under conditions of approximately constant mmf. Using the circuit of Fig. 5, consider the start of the conducting half cycle for rectifier A. Core B has just come out of saturation leaving only the control mmf due to i_c attempting to reset the core B. Since exciting current only is flowing through R_L, the voltage drop across it is almost negligible. Thus flux reset can be accomplished in core B at a maximum rate approximately equal to the voltage e_1 until core A "fires". With reference now to Fig. 6, if reset rate of the core for the given d-c control mmf is capable of inducing a voltage equal to or greater than the instantaneous value of the voltage e_1, rectifier B will conduct, and the "stiffness" of the line voltage will limit the rate of reset, i.e., e_G in Fig. 5. This phenomenon has been termed "backfiring".[1,3] By considering this phenomenon and referring again to Fig. 6, it can be seen that the least useful type of reset characteristic curve is one which rises very steeply initially only to decline rapidly later on. Perhaps the most generally efficient shape for the reset curve is one which is sinusoidal, just fitting the available (line) voltage for reset.

After core A "fires", the allowable (or available) voltage limit on reset jumps to roughly $2e_1$.

The action following the instant of firing will be entirely different for other circuits, such as the "doubler" or the full-wave bridge circuit. With reference again to Fig. 5, it frequently occurs that for typical reset mmf's, the reset rate toward the end of the half-cycle attempts again to exceed the available voltage limit, $2e_1$. This causes rectifier B to conduct again as in "back-firing". In other circuits where the available reset voltage limit is much less, the action is more severe. Roberts has implied[1] the difference in shape of the flux reset curve of Fig. 3 causes noticeably different amplistat performance between two cores which by other core tests were predicted to give the same performance. This certainly appears to be the case, and further detail is provided in Ref. 4. "Back-firing" varies greatly with core materials, as might be expected. It also varies considerably from one sample to the next for a given material. In some cases "back-firing" occurs in the middle of the cycle, when the available voltage is in its maximum region. Variations in back-firing are extremely difficult to predict from any core tests now known to be in wide usage. Yet variations cause differences in amplistat performance. The mechanics of various

circuit operations are covered in detail by Storm[2] and Lord[3]. However, no explanation is presented as to why the reset rate-of-change of flux proceeds either slowly enough so that rectifier B does not conduct or proceeds fast enough to "back-fire". The qualitative explanation lies in the type of flux reset characteristic, samples of which are shown in Figs. 2, 3, and 4.

Predicting amplistat characteristics from hysteresis loops would be difficult indeed (except for the one low impedance case noted above). Consider Fig. 6, which is a study of flux reset in a half-wave high impedance control circuit amplifier, the basic element of an amplistat. The d-c control characteristic normally obtained is shown in Fig. 6 (B). To obtain the oscillograms redrawn in Fig. 6(A), the core was first driven into positive saturation, similar to amplistat operation, then reset at the same three values of constant d-c mmf indicated in Fig. 6(B) by points 1, 2, and 3 on the control characteristic. The sine arch in Fig. 6(A) shows the reset available voltage limit (line voltage). Wherever the dB/dt is above the super-imposed available limit, back-firing can be presumed to have occurred, accounting for the output value observed in Fig. 6(B). Note that given time much greater than 1/120 second, any of these three values of mmf shown would have reset the flux all the way. Other core materials can be expected to show entirely different performance. Why a reset characteristic approximating a sine arch is an efficient and desirable shape can be implied from Fig. 6.

Considering the odd and unusual reset characteristics of Fig. 2, 3, and 4, one almost wonders how it is possible to achieve an amplifier with a linear portion in its characteristic. To be truthful and accurate, it is not easy—not in any sense of the word, as anyone will attest who has engineered accurate instrument amplifier systems. The author has found a little luck to be as indispensable as copious amounts of feedback. Perhaps this is because a linear characteristic is fundamentally the sum of two non-linear characteristics, namely of the core and of the rectifiers.

IV. QUALITY CONTROL TESTING

General

Quality control of magnetic amplifiers can be expected to increase its dependence upon core measurement techniques in the future as improved rectifiers become available. Several core manufacturers have already developed a remarkable degree of control over their products. But there is a natural tendency to promote core grading based on hysteresis loop properties. For example, an ingenious circuit originated by Patrick and Jansons[7] has been put into practice by one core manufacturer. It measures accurately the nominal *sine current* hysteresis loop properties, H_c, U_D, B_R, B_{MAX}, etc., as shown in Fig. 1. These measurements are of proven value in core matching, and, of course, can be used as a basis for arbitrary grading. However, this does not at all represent the conditions imposed upon an amplistat core. Another manufacturer has used a different test, which has proven merit in core matching and grading. This circuit is somewhat similar to those of Conrath and Roberts in that the core can be driven realistically far into saturation, then reset to *any* desired level under sine wave of current conditions by varying the resistance in series with the reset coil. But again this is not what an amplistat core sees, thus limiting

its usefulness in quality control. The work described by Conrath[6] and Roberts [1,8] has been a great contribution to the quality control art because the circuits test sample cores under conditions partially similar to amplistat operation. Instrumentation is somewhat difficult, however, and there are technical shortcomings which will now be discussed.

Peak Setting MMF

It was shown in the preceding sections why an amplistat core test *requires* that the reset mmf used be the same as in actual operation. It is particularly important that the core under test be driven (set) into about the same degree of positive saturation as will occur in the actual operation of the amplistat for which it is intended. If it is not, the reset characteristic observed may show a pronounced difference. Driving the core further into saturation will, for example, widen the hysteresis loop. From Fig. 5 it can be seen that the load resistor will determine the peak mmf applied. When the amplistat conducts over more than 90 degrees, the peak current is always the same being equal to the peak value of e_1 divided by the load resistance, R_L. When it fires later than 90°, the peak current is less as the conducting angle becomes less, its value being proportional to the sine of the conducting angle for values less than 90°. Thus, for the core test to be realistic, the setting value of mmf *cannot* be fixed when the conducting angle is less than 90°, but must vary with the sine of the angle.

Backfiring

The discussion in the previous section showed that "backfiring" can almost always be expected. In most applications it is an essential factor in predicting performance. Thus for a core test to be realistic backfiring must be taken into account.

Resetting MMF

In the absence of backfiring constant reset mmf (i.e., constant control current) would be a realistic test condition for the d-c control amplistat, high impedance case. But because backfiring must usually be expected, something must be done to net control (reset) mmf to make a core test realistic.

A New Approach to Core Testing

Analysis of the shortcomings of various core-test philosophies[1, 5, 6, 7] leads to the conclusion that there is no practically accurate substitute for imposing on the core under test:

1. The actual peak setting mmf encountered in the finished amplistat product.
2. The same net reset mmf vs. time pattern.
3. The limitation on the allowable reset voltage, characterized by backfiring.

Rapid, production-type of testing requires some sort of "plug-in" test fixture. Such a device is rarely capable of placing more than twenty turns around the core; perhaps ten of these turns can be employed as a simulated gate winding. At typical voltages of 4 millivolts per turn, the test supply volts would then be 40 millivolts, a figure too low by a factor of 100 to be suitable for testing with any rectifiers known today.

However, induced voltage signals at this level are quite easy to amplify electronically with high accuracy. Thus it becomes quite a straightforward

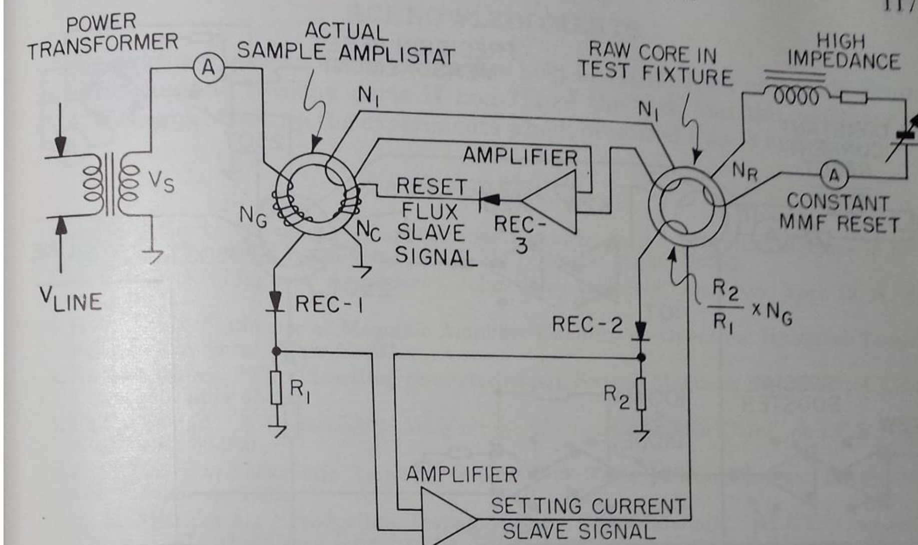

Fig. 7—Slave system philosophy for testing amplistat cores.

matter to slave the flux in one core to the flux in a core under test. Since mmf is produced by current, different currents can easily be slaved together in any desired ratio by comparing the drops across suitably chosen shunts.

By using this approach Fig. 7 shows why it is a straightforward matter to reproduce true and exact amplistat operating conditions upon a core under test; and secondly, to repeat back the performance of the core without "loading" or disturbing the circuit in any way. This approach will seem conventional to those familiar with computers, although to others it may appear much more difficult than it actually is. The slave amplistat core loses its identity in the circuit, being forced merely to repeat instantaneously the reset flux changes occurring in the test core. Different amplistat circuits will require different test setups, but the philosophy will be the same. The basic amplistat half wave element is used for Figs. 7 and 8 because it is the simplest case.

To visualize the operation of the circuit of Fig. 7 let us start at the time the slave amplistat fires. The setting current on the test core is regulated by the amplifier so as to maintain the instantaneous value of voltage drop across R_2 equal to R_1, the latter being very much larger than R_2. However, this setting current amplifier is not allowed to reverse itself because of the rectifiers, and thus it will not interfere with reset. From this it can be seen that the peak setting mmf is always exactly equal to the real amplistat value. Reset begins as the line voltage goes through zero, the flux resetting signal forcing the slave amplistat flux change to induce a voltage in the pickup coil, N_1, which is equal to that in the pickup coil, N_1, on the test core, with which it is compared. Should the reset flux in the slave be driven fast enough to cause backfiring, forward current will flow through the load resistance. This then commands forward current on the test core bucking the reset mmf as necessary to slow down its reset rate to that available in the slave. Thus the action on the test core is identical to actual backfiring, and the test core is truly being tested under exact amplistat circuit conditions.

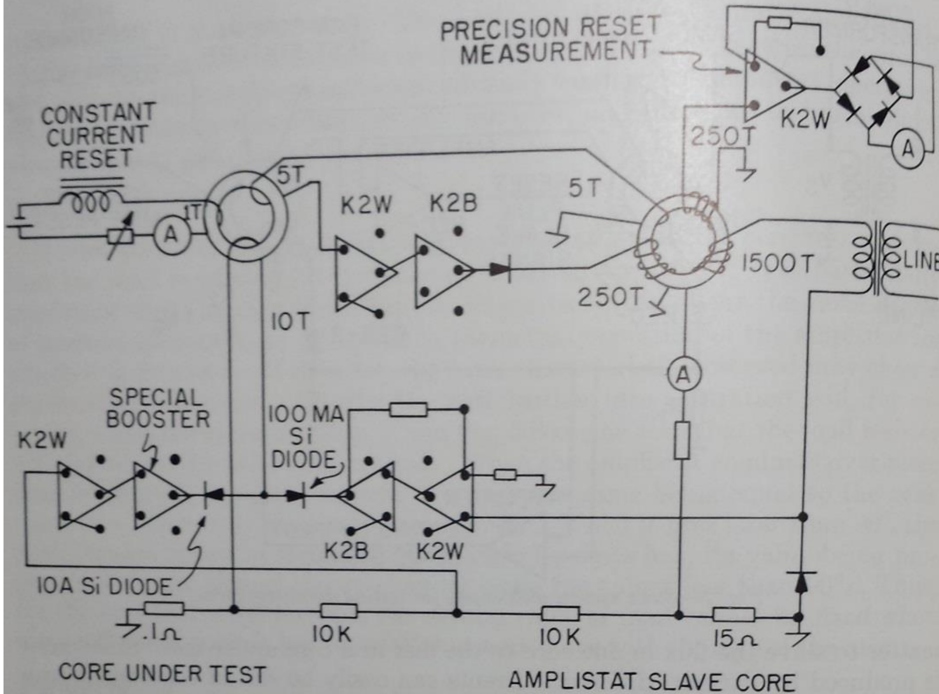

Fig. 8—Proposed schematic of slave system using Philbrick Operational plug-in amplifiers.

Figure 8 shows a proposed core test set up for a typical amplistat circuit using conventional plug-in amplifiers, such as those made by G. A. Philbrick Company, types K2W and K2B, and one special boost amplifier. The circuit is operationally similar to that in Fig. 7 except that an amplifier is added to obtain a more refined measure of backfiring. This is achieved by using a K2W amplifier to observe when the rectifier in the slave amplistat load circuit is on the threshold of conduction. The use of operational plug-in amplifiers permits extremely simple circuitry so far as the test equipment goes, as can be seen. The plug-in units have reversible output characteristics, symmetrical around zero input signal. Their drift, in terms of input signal voltage, is usually less than 3 millivolts, even without stabilizers around them. The drift is only a small fraction of a millivolt with stabilizers. Figure 8, as shown, does not give a direct meter reading of amplistat gain. However, by using a low frequency oscillator to superimpose an a-c modulation upon the reset mmf, the gain can be determined by simply measuring the low frequency a-c component in the slave output.

Conclusion

Various test circuits have been discussed, pointing out principal shortcomings, and a test technique has been proposed to overcome them. This technique is not without its share of complications, although quite straightforward to those familiar with plug-in operational amplifiers. Those responsible for quality control practice will have to decide ultimately whether new improved rectifiers justify the tighter core quality grading now possible.

ACKNOWLEDGMENTS

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